MEASUREMENT OF HORIZONTAL DISPLACEMENTS IN EUROPEAN COALFIELDS

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Abstract

The paper gives the methods for surveying horizontal deformations due to underground mining activities. The measurement techniques were compared in view of different coal-basins across Europe, Germany and Poland in particular.

1. Introduction

The European hard coal mining faces a crisis. This problem affects both West European (Great Britain, Germany, France) and East European countries (Poland, Czech Republic, Hungary, Ukraine). In Poland hard coal was and in the nearest 20 years will be the basic energy fuel. Thus, hard coal mining will have to be put among the basic branches of economy. However, economic changes, globalization, development of new technologies and development of environmental consciousness necessitate the restructuring and modernization of the Polish mining. One of the most vital factors affecting mining industry is the degree of social acceptance. This, however, is strongly influenced by the negative environmental impact of mining. The environmental impact is usually associated with air pollution, discharge of mine's waters, noise. Deformations and damage done to houses due to mining activities are often neglected.

By the time GPS systems were introduced, the deformation indexes were determined based on two types of measurements, i.e. height measurements (leveling) and longitudinal measurements. GPS for surveying mining areas was a real revolution in the designing and analysis of displacements. Thanks to this system it was possible to quickly and adequately determine the displacement/strain vector of individual points on the surface, thus creating good possibilities to monitor deformations within the whole displacement over the extraction area.

The paper shows limitations resulting from the use of traditional measuring methods on the background of GPS-based techniques. A new approach to the designing and surveying in mining areas has been put forward.

2. European Coalfields

The demand for mineral materials began to increase with the development of Europe. Since the 17th century coal extraction had played a more and more prominent role. In the age of big demand for coal, hundreds of mines scattered across numerous coalfields around Europe operated. Coal was extracted in almost every country in Europe. Presently, despite the constant need for coal (growth of world's production) the Europe's coal production decreases. In the recent 20 years a 43% drop of coal production has been observed. A number of factors are responsible for this state, but the most crucial is the high cost of coal production (manpower, difficult geological situation, etc.). Thus, many coalfields in Europe had to be decommissioned. The remaining ones still operate but the imperative to keep them going is not so much economic as social and strategic.

The Europe's coal constitutes about 25% of the world's resources (Mokrzycki, 2000). The assessed coal resources in Europe are:

- Geological - about 1020 billion tones
- Balance – about 231 billion tones.

The group of the biggest coal producers in Europe consists of the following countries:
Czech Republic, Germany, Great Britain, Poland, Russia and Ukraine. The biggest European coal basins (surface, resource and number of coal seams per basin) have been listed in Table 1 (Gabzdyl, 1994; Zeleznowa et al., 1983). The location of these basins has been presented in a map of Europe.

Table 1. List of the biggest European coal basins

No	Basin name	Country	Surface	Resource	Number of coal seams
			[1000 km^2]	[Billion tones]	
1	Moscow	Russia	120	17	1-3
2	Donec	Ukraine	60	54	~130
3	Upper Silesian	Poland	6.1	57	~250
4	Ostrava-Karvina	Czech Republic	1.6	4.5	~250
5	Ruhr	Germany	5	213*	45-60
6	Saar	Germany	0.8	9	50-100
7	Lothringe	France		4	~70
8	Northumberland	Great Britain	4.2	2.1	10-13
9	Nottinghamshire	Great Britain	2.3	14	30-42
10	South Wales	Great Britain	2.6	9.5	12-20

*Resources to 2000 m of depth in seams over 0.6 m thick

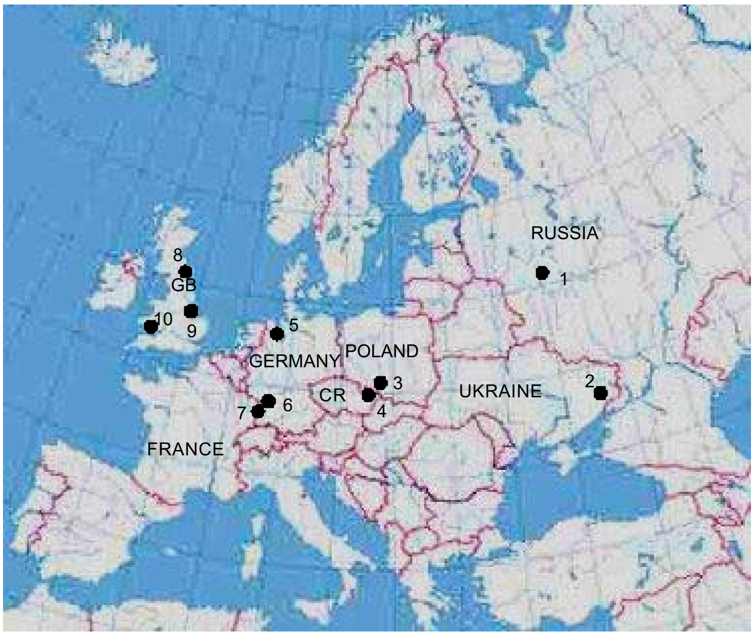

Fig. 1. Map of distribution of the most important European coal basins

It can be concluded from the above data that the European coal resources still enable coal production for many future years. Coalfields occupy a considerable area, often coinciding with densely developed areas and utilities, which should necessitate the measurement of deformations on considerable areas.

3. Measurement of deformations

The development of mining and intensity of production urged the measurements of unfavorable mining impact on the surface. Originally, the so-called subsidence index was measured with the surveys and analyses. Unfavorable influence of mining was solely attributed to subsidence and its derivatives (surface tilt).

With the increasing depth of exploitation and advancement of survey techniques and tools, the horizontal deformation indexes started to be observed. The first observations were made in about 1901 in the Ruhr Basin, near Essen and Bochum (Klenczar, 1952). Presently, the measurements of horizontal deformations are of great significance owing to the fact that they may strongly affect the hazards of cubature objects.

Horizontal displacements of measurement points distributed over the mining area can be determined in two ways:

- as *absolute horizontal displacement*, i.e. change of location of measurement point with respect to the assumed and stable co-ordinates system; the section linking initial coordinates with the end position of the measurement point are assumed to be a linear displacement.
- as *relative horizontal displacement*, i.e. change of distance between end points of the measurement line; there is no need to assume a co-ordinates system. In such a situation points staying beyond the displacement area should be defined.

The most popular survey technique applied in the Upper Silesian Coal Basin was the measurement of length of sides along the assumed (possibly straight) measuring line (Hejmanowski, Kwinta, 1997). The processing of the length measurement data resulted in obtaining relative horizontal displacements. As already mentioned, a stable point had to be defined in such a case (i.e. a selected stable point should stay beyond the area of displacements). Unluckily, such a point is hard to find. Traditionally, the determined displacements are burdened with a systematic error. Based on the results of the measurements it is possible to calculate the relative horizontal displacements with the use of the formulae:

$$\Delta d_{i-1,i} = d^{a}_{i-1,i} - d^{0}_{i-1,i} \tag{1}$$

$$U_i = U_0 + \sum_{k=1}^{i} \Delta d_{k-1,k} \tag{2}$$

$$x_i = x_{i-1} + d^{0}_{i-1,i} \tag{3}$$

where: $d_{i-1,i}$ - measured length of section between points i-1 and i.
U_i - displacement of the 1-th point
x_i - coordinate along the measuring profile
a,0 - numbers of measuring series

A conclusion can be drawn from these measurements: the obtained results will be reliable only at special regime, e.g. measuring line is straight and parallel to the direction of advancement front. Each change of direction of measuring side (unknown subsidence perpendicular to the measuring line) may lead to considerable discrepancies between the measured and actual displacements of points along the measuring line.

The differences in the determined relative and absolute displacements calculated for the same case are presented in Fig. 2.

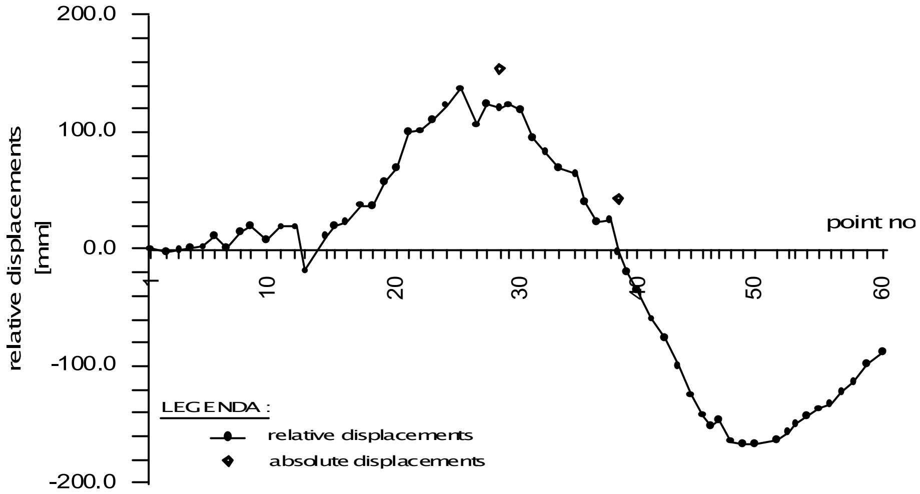

Fig. 2. Determined relative and absolute horizontal displacement registered along the measuring line.

The differences between relative and absolute horizontal displacements can be established from the Figure 1. The differences in the region of maximum deformation indexes are especially significant. Here the discrepancies are equal to 15%.

The measurement of absolute horizontal displacements should be based on stable points deposited outside the displacement area. By the time such modern electronic systems as GPS appeared, this type of measurements had been rare. This was the case for two reasons: relatively low accuracy and labor-consumption (very costly measurements). The following basic constructions were used: angular-linear net, polygonal traverse, micro-triangulation nets and photogrammetry methods.

The appearance of GPS methods created new possibilities for measuring displacements. The displacements could be measured with GPS in two ways:

- Determination of location of individual random points, distributed in characteristic places, from which we want to get information; here, for example the static-quick method can be used.
- Determination of co-ordinates of measuring points; based on them polygonal or angular-linear net can be generated. Using the static-quick method, the points can be determined and on this basis the measuring points selected and disposed on buildings and other objects subject to mining impact.

GPS measurements are relatively accurate (even below ± 5 mm). One series can be measured very quickly (even within a day) but this depends on the accessible number of receivers. It follows from the measurements in the Ruhr Basin that having three receivers one can measure as much as 60 GPS points. (Ballhaus et al., 2000).

When measuring absolute horizontal displacements we determine new components of displacement/strain vector of the measuring point in the current measuring series with respect to the results of measurements for the initial series. As a consequence we obtain displacements in two perpendicular directions. On this basis it is possible to determine the maximum value of displacement, and to determine the displacement of the point in an arbitrary assumed direction α.

$$\begin{cases} u_{xi} = x_i^a - x_i^0 \\ u_{yi} = y_i^a - y_i^0 \end{cases} \tag{4}$$

$$u_{i\max} = \sqrt{u_{xi}^2 + u_{yi}^2} \tag{5}$$

$$\varphi_{ui\max} = \operatorname{arctg}\frac{u_{yi}}{u_{xi}} \tag{6}$$

$$u_{\alpha} = u_x \cos\alpha + u_y \sin\alpha \tag{7}$$

Such a way of measuring deformations is commonly applied in the Ruhr Basin (Ballhaus et al., 2000). Measuring points (random points) measured with GPS are selected over the extraction areas in the characteristic points. Based on such periodical measurements it is possible to trace the change of location of individual measuring points and development of extraction. Economically, such measurements are more profitable. Technically, the information is quickly obtained in places that are of significance to us.

In Poland (Upper Silesian Coal Basin) the GPS system has been recently introduced for the measurement of deformations in mining areas (1993). Measurements on measuring lines are still more popular. Points determined with the GPS method are usually used for making geodesic benchmark or as nodes.

Deformation of a surface is a change of location of points on the surface. This deformation is described by two measures: linear and non-dilatational deformations. The deformation measures are local parameters ascribed to the point enclosed in an infinitely small element. The state of deformation in that point is determined, provided deformation measures can be defined in an arbitrary direction. The measure of a linear and non-dilatational deformation make up a tensor of the state of deformations in a given point (8).

$$T_{\varepsilon} = \begin{bmatrix} \varepsilon_x & \dfrac{\gamma_{xy}}{2} \\ \dfrac{\gamma_{yx}}{2} & \varepsilon_y \end{bmatrix} \tag{8}$$

where: T_{ε} - deformation/strain tensor
$\varepsilon_x, \varepsilon_y$ - linear deformation along the axes x and y
$\gamma_{x,y,}, \gamma_{yx}$ - non-dilatational deformation; both parameters are equal

The elements of deformation/strain tensor depend on the selected co-ordinates system. If it is changed, the elements undergo transformations analogous to the vector's co-ordinates. The so-called main transformations ε_{max} and ε_{min} and extreme non-dilatational deformations γ_{ekstr} remain unchanged in the transformation. The main deformations are extreme linear deformations in the function of direction, whereas extreme non-dilatational deformations are maximum non-dilatational deformations. These parameters can be written in the following form:

$$\varepsilon_{\max} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{1}{2}\sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + 4\gamma_{xy}^2} \tag{9}$$

$$\varepsilon_{\min} = \frac{\varepsilon_x + \varepsilon_y}{2} - \frac{1}{2}\sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + 4\gamma_{xy}^2}\ , \tag{10}$$

where:

$$\gamma_{\max} = \pm\frac{1}{2}\sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + 4\gamma_{xy}^2}$$ - extreme non-dilatational deformation.

Deformations in an arbitrary direction α (angle α measured counter-clockwise in relation to axis x) can be determined from the relations:

$$\varepsilon_\alpha = \varepsilon_x \cos^2\alpha + \varepsilon_y \sin^2\alpha + 2\gamma_{xy} \sin\alpha \cos\alpha \tag{11}$$

$$\gamma_\alpha = \left(\varepsilon_x - \varepsilon_y\right)\sin\alpha \cos\alpha - \gamma_{xy}\left(\cos^2\alpha - \sin^2\alpha\right) \tag{12}$$

Horizontal deformations should be determined from measurements carried out on infinitely small measurement bases. Thus basically, deformations should be defined from tensometric measurements. In practice, horizontal deformations are mainly obtained from survey measurements, made on relatively long measuring bases. Thus obtained deformations are only averaged actual data (Kwinta, 1998).

Let's analyze the relation between displacements and horizontal deformations. First, let's consider an infinitely small element of surface of size dx and dy (Figure 3). In the process of deformation individual points of this element have been displaced. Therefore, it is possible to determine the change of co-ordinates of points being the nodes of the element. The magnitudes of displacement of individual nodes were presented in Figure 3. For instance, originally point A was in the origin of the selected co-ordinates system, but in the course of deformation it was moved towards the axis x by some value u and towards axis y by v to form point A'.

Through the analysis of deformations of the analyzed elementary rectangle it is possible to obtain formulae for deformations in the direction of axes of the assumed co-ordinates system and non-dilatational deformations. Thus acquired geometrical relations (13), (14) and (15) are Cauchy's equations:

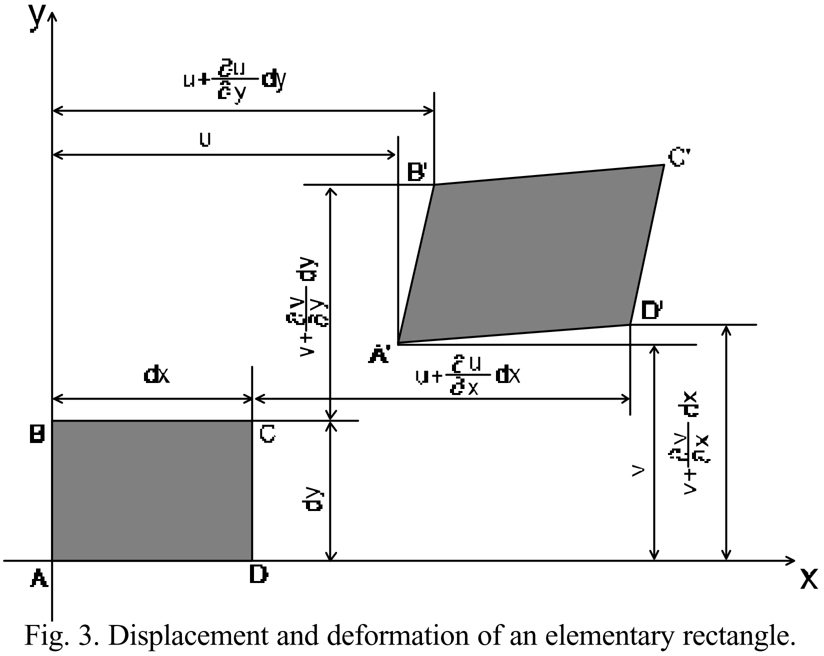

Fig. 3. Displacement and deformation of an elementary rectangle.

$$\varepsilon_x = \frac{\partial u}{\partial x} \tag{13}$$

$$\varepsilon_y = \frac{\partial v}{\partial y} \tag{14}$$

$$\gamma_{xy} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \tag{15}$$

Linear horizontal deformations in the direction of axes of the assumed co-ordinates system and non-dilatational deformations can be determined with these equations. With these data and equations (9) and (10) the tensor of flat deformation/strain can be established. In the case of traditional measurement methods, horizontal deformations are determined from the measurement of length of measurement line in the individual series (in comply with the definition of a linear deformation), equation (16):

$$\varepsilon_i = \frac{d_i - d_0}{d_0} \tag{16}$$

where: ε_i - mean deformation of a section in the i-th measurement series
d_i - length of section in the i-th measurement series
d_o - original length of the section

Using the above relations, the deformation in a given section can be defined, but only in the direction determined by the assumed co-ordinates system. In most cases the determined deformation will not coincide with the maximum value. To determine the main deformations, special constructions called rosettes can be assumed. This is a system of three measurement sides making up a triangle. Basically, two types of such a construction can be distinguished, i.e. rectangular (equilateral, isosceles triangle) and delta (equilateral triangle) rosettes. What is obtained from a geometrical construction in the form of a rosette is a system of three equations with three unknowns. By solving this system of equations it is possible to define deformations in the direction of axes of the co-ordinates system and non-dilatational deformation. For delta rosette we get:

$$\begin{cases} \varepsilon_x = \varepsilon_1 \\ \varepsilon_y = \frac{1}{3}\left[2\left(\varepsilon_2 + \varepsilon_3\right) - \varepsilon_1\right] \\ \gamma_{xy} = \frac{\sqrt{3}}{3}\left(\varepsilon_3 - \varepsilon_2\right) \end{cases} \tag{17}$$

where: ε_i - deformation along individual sides of an equilateral triangle.

Having defined components of deformation/strain we can calculate main deformations and maximum non-dilatational deformation/strain from equations (9) and (10).

Let's define horizontal deformations when measuring displacements of absolute measuring points, e.g. with the use of GPS satellite techniques). Here deformations can be obtained from Cauchy's equations (13) and (14), substituting differentials with increments (Kwinta, 1998).

A system of two measuring points enables one to determine only linear deformations in two perpendicular directions. Regardless the assumed co-ordinates system, the sum of these two deformations is stable. To determine the deformation/strain tensor it is necessary to have a system of three non co-linear measuring points.

Concluding, to define the full state of deformations/strain in a given area, a system of three measuring points is necessary. Such an approach is not profitable because the number of points needed for the measurement is three times bigger than for horizontal displacements. This has a negative effect on the cost of inspection of the deformation process and the time in which the deformations are measured. A solution to this problem can be a combination of various geometrical constructions in the same area. The principal element of inspection in such a case would be an observation line measured with the newest methods; for an area with significant surface objects on it - measurement rosettes should be used.

Generally, no deformations can be determined from displacements measured in random points where the distance between the points is too big. The analysis of semi-variograms shows that at distances as small as 0.2 H (H - depth of extraction) the effect has a random character and the obtained values are of no physical significance. It follows from the Polish experience that the distance between the points should not exceed 25 m, which is about 0.05H for the average depth of exploitation in the Polish conditions. However, due to the high cost of measurements and the considerable range of extraction, such a dense geodesic benchmark is out of the question. Therefore, a very interesting concept should be taken into consideration, i.e. measure displacements in random points and employ mathematical prediction models for determining deformations. To obtain a full state of deformations/strains, a series of calculations have to be performed to go from displacements in random points to the complete deformation/strain field.
Of course, there arise a number of problems to be solved, e.g.:

- Determine the density of random points to define horizontal displacements
- Establish interpolation methodic

4. Conclusions

The authors of the paper present the survey-based development of methodic used for determining displacements and horizontal deformations. This development is conditioned by the accessibility of measuring equipment, financial aspect and technical consciousness of the contractor. The possibilities to obtain data for a flat state of displacements and deformations have been shown. In the authors' opinion, they should rely on new measuring techniques and modification of the observation net.

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